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Sprinkler Fire Suppression Algorithm for HAZARD

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United States Department of Commerce
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ABSTRACT

Measurements of the heat release rate of a fully involved square base wood crib both before and during fire suppression with water spray from commercial sprinklers were used to develop a correlation for the exponential decay time constant (τ) of the fire heat release rate from the value at sprinkler actuation. This correlation is the basis for prediction of limits for heat release rates of furnishings during fire suppression. For 0.61 m square base wood cribs that are 0.61 m in height, the time constant varies with spray density ($\dot{w}''$) as: $\tau = 3.0\ (\dot{w}'')^{-1.85}$. Using this result, the time constant for suppression at a sprinkler spray density of 0.07 mm/s is 410 s.

1. INTRODUCTION

Many of the current quantitative prediction methods for fire hazard analysis are very limited in ability to include fire suppression. For example, in HAZARD I [1] the time of the first sprinkler actuation can be calculated, but there is no method to assess the fire suppression effects of water spray on the fire. The phenomena of fire suppression with water, including water spray interacting with fire gases and fuel elements, is an extremely complex physical, thermal and chemical problem well beyond current engineering abilities to predict in detail. It is possible to develop a conservative estimate of the effectiveness of sprinklers in reducing the heat release rate of furnishing fires based on measurements of wood crib fire suppression with sprinklers. Data for crib fire suppression are taken from previous studies conducted by NIST for the U.S. General Services Administration and the U.S. Fire Administration.

2. ALGORITHM SCOPE

Successful fire suppression is the process that ends in extinguishment. Many of the investigations of fire suppression have been conducted to determine the critical conditions for extinction [2,3,4,5]. Unfortunately, these experiments do not provide the information that is needed to understand the rate of fire suppression. As discussed by Evans [6,7], measurements of the rate of fire suppression or duration of the suppression process before extinction occurs

are critical to the development of engineering models for the suppression process. Prediction of the rate of fire suppression, as indicated by the time dependent reduction in the heat release rate of the fire, is the central feature of this sprinkler fire suppression predictive method.

Sprinkler actuation calculations enable the prediction of the time that fire suppression will begin. From the time of sprinkler actuation, water is sprayed into the area surrounding the fire. The only effect of the sprinkler spray included in this model is its effect on the heat release rate of the fire. It is acknowledged that this represents a minimal step forward in the assessment of the full impact of sprinklers on room fires, but it is also an important one. The heat release rate is the most important single characteristic of a fire in the determination of hazard.

3. FIRE SUPPRESSION PREDICTION

This fire suppression prediction method provides a means to estimate the reduction in the heat release rate of a fire (or fuel mass loss rate) based on the results of experiments in which fully involved square base wood crib fires were suppressed with water spray from common pendent sprinklers. The assumption needed for generalization of the prediction is that the fire suppression of all fuels have the same degree of resistance to fire suppression as a wood crib. This has been shown to be a conservative assumption from the standpoint of hazard prediction for a range of office furnishings by Madrzykowski and Vettori [8].

Measured reductions in heat release rate [8] during suppression of unshielded office furnishing and wood crib fires, as shown in figure 1, demonstrate the large range of results for fuels of different materials, geometries, and preburn times even though all of the tests were conducted at nominally the same sprinkler spray density (0.07 mm/s). Some of the furnishings, such as the sofa and workstation II, were extinguished rapidly. Others, like the wood cribs and workstation I took many hundreds of seconds. The presentation of the data in figure 1, suggests that the post sprinkler actuation heat release rate roughly follows an exponential decay, often after an abrupt decrease immediately following sprinkler actuation. Based on observations during the tests, this initial abrupt decrease seems to be associated with the rapid extinguishment of burning surfaces that are fully exposed to the spray. In general, furnishings with a large burning surface areas exposed to direct spray impingement were extinguished easily (small time constant); those with partially shielded and deep seated fires were more difficult to extinguish (large time constants). Values for the decay constant, recorded in Table 1, range from 9.1 s for the easily extinguished sofa fire to 713 s for the more difficult to extinguish workstation I fire. It is beyond present capabilities to predict the time constants for the reduction in heat release rate of furnishings fires during suppression with water spray from sprinklers. However, Madrzykowski and Vettori [8] observed that the reduction in heat release rate of all of the furnishings are bounded by the curve:

$$\dot{Q}(t-t_{act})/\dot{Q}(t_{act}) = \exp\left[-(t-t_{act})/435\right] \qquad (1)$$

where

$\dot{Q}(t\text{-}t_{act})$ = post sprinkler actuation heat release rate of the fire, kW

$\dot{Q}(t_{act})$ = heat release rate at the time of sprinkler actuation (t_{act}), kW

as shown in figure 1. Use of this limit in cases where the fuel is not shielded from the water spray, provides a means to calculate a conservative bound, meaning minimum expected reduction in heat release rate of a fire being suppressed by a sprinkler. This result is appropriate for spray densities greater than or equal to 0.07 mm/s. This method does not account for variations in sprinkler water spray density, and the suppression capabilities of all sprinklers are predicted to be the same. The method constitutes a zeroth order prediction of sprinkler fire suppression.

The next logical step in the development of a sprinkler fire suppression prediction method is to account for the effects of variations in spray density. The experiments conducted by Walton [9] may be used to access the effect of different sprinkler water spray densities on the heat release rate during suppression of wood crib fires. Walton used two different wood crib geometries in his experiments; (38.1 mm x 6 x 8 x 16)[a] referred to by the crib height of 305 mm, and a crib twice as tall (38.1 mm x 6 x 16 x 16) referred to as 610 mm. All of the data collected by Walton in experiments using 305 mm and 610 mm wood cribs are shown in figures 2 and 3, respectively. These figures also include experiments in which the crib was burned without water application (Free Burn). As in the study of furnishings, these measurements can be recast into the form of $\dot{Q}(t\text{-}t_{act})/\dot{Q}(t_{act})$ each of which can be bounded by a curve of the form exp $[-(t\text{-}t_{act})/\tau]$, where τ is a time constant for the post-sprinkler actuation heat release rate reduction. In some cases, this one parameter function is actually a good representation of the time dependent variation in rate of heat release, for both the 305 mm and 610 mm crib fires, see figures 4 and 5. In other cases, the data were not fit well by the assumed exponential functional form, but only bounded by it as in figure 6. In experiments with large spray densities, the crib fire is extinguished rapidly. As data was recorded every 10 seconds, in the case of rapid extinction, as shown in figure 7, very few data points are available for determining the time constant for the heat release rate during fire suppression. At small spray densities the water did not have a measurable effect on the heat release rate of the crib fire. For that reason Walton's data for the 305 mm crib fire suppression at a sprinkler spray density of 0.013 mm/s and the 610 mm crib fire at 0.14 mm/s and 0.039 mm/s were not included in the analysis. For the remaining crib fire experiments, Table 2 lists the apparent decay time constant for the heat release rate during suppression and the estimated uncertainties. In figures 4-7, the exponential function used to determine a value for τ is shown the dashed-straight-line. The estimated uncertainties are shown as dotted-straight-lines.

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[a] Square base cribs are specified in notation a x n x N x l/a, where (a) and (l) are the stick thickness and length, n is the number of sticks per layer and N is the number of layers.

Earlier studies of wood crib fire suppression by Tamanini [10] have shown that the time to extinction was proportional to the water application rate per unit exposed surface area of the crib. The variation of the exponential decay rate with sprinkler spray density is shown in figure 8. To correlate the data from the two crib geometries, spray density is normalized using the crib height, which for this study is proportional to the exposed surface area used by Tamanini [10]. It can be seen from figure 8 that the two sets of data from Walton's study are brought together by dividing the spray density by the crib height (either 305 mm or 610 mm). As expected, the time constant for the exponential decay in the rate of heat release, decreases (rapid suppression) as the water spray density increases. Although the data is scattered, a least squares fit yields a formula for the variation in time constant representing the reduction in heat release rate of wood crib fire during suppression with sprinkler sprays within ± 50% as:

$$\tau = 2.0 \times 10^{-5} (\dot{w}''/H_c)^{-1.85} \tag{2}$$

where

τ = time constant (s)
$\dot{w}''$ = spray density (mm/s)
H_c = crib height (mm)

Substituting 610 mm for H_c in equation (2) yields:

$$\tau = 3.0 (\dot{w}'')^{-1.85} \tag{3}$$

This formula constitutes a generalization of the results of Madrzykowski and Vettori, for one spray density (0.07 mm/s), to other generally greater spray densities. For a spray density of 0.07 mm/s, equation (3) yields a predicted time constant for suppression of 610 mm wood cribs of 410 s. Considering the scatter in the data (figure 8), this value may be considered equivalent to the 435 s time constant reported by Madrzykowski and Vettori as a bounding value to the measured heat release rate of furnishings during suppression. The results for the 305 mm crib used to support the development of equation (2) are not used for any other purpose. Using the value of τ from equation (3), for the purpose of conservatively estimating the heat release rate of unshielded furnishing fires during suppression, the following equation is recommended:

$$\dot{Q}(t-t_{act}) = \dot{Q}(t_{act})\exp[-(t-t_{act})/(3.0 (\dot{w}'')^{-1.85})] \tag{4}$$

Although unproven at this time because furnishing fire suppression data like that reported by Madrzykowski and Vettori is currently available at only one spray density (0.07 mm/s), equation (4) is assumed to bound the heat release rate of furnishing fires during suppression at other spray densities. Equation (4) represents an improvement in predictive capabilities beyond that developed by Madrzykowski and Vettori [8] by adding the effect of variations in

sprinkler spray density. As seen in figure 8 and also found by Tamanini [10], at lower water application rates (spray densities), the power-law dependence applicable for larger water application rates (spray densities) over predicts the long times to extinguishment. The 610 mm cribs had sufficiently long burn times to evaluate suppression time constants as large as 500 s. For the purpose of hazard analysis, sprinklers that reduce the heat release rate of fires at a slower rate may not be of practical concern. Most of the data analyzed in this study were from experiments in which the sprinkler spray density was greater than 0.07 mm/s.

4. CONCLUSIONS

A method has been developed that can increase the capabilities of the HAZARD I and other room fire models to predict, in a conservative manner, the reduction in fire heat release rate of furnishing fires during suppression with water spray from sprinklers. The method falls short of predicting all of the consequences of sprinkler sprays on building fires. In particular, the model does not consider the interaction of the spray with the fire driven gas flow. Nevertheless, incorporation of this predictive method in the HAZARD I model will provide users with a means to demonstrate the minimum effect of installed sprinklers on the development of hazard associated with unwanted fires in buildings.

5. ACKNOWLEDGEMENTS

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Furnishing Package	Q_{act} (kW)	Decay Time Constant (s)
Sofa (vinyl covered, polyurethane foam cushioned)	280	9.1
Workstation II (office partitions, wooden desk, ABS bucket chair, computer terminal, and assorted papers and books)	700	21.3
Papercart (canvas hamper filled with shredded paper and polyethylene bags)	700	21.7
Executive Office (wooden desk, polyurethane foam padded chair, upholstered chair with neoprene padding, computer terminal, and assorted papers and files)	545	30.4
Office II (wooden desk, wooden reference table, computer terminal, cardboard paper recycling box, and assorted papers and files)	425	41.3
Office I (wooden desk, wooden reference table, computer terminal, boxes with paper, assorted paper, books, and files)	1085 950	230
Workstation I (office partitions, wooden desk, ABS bucket chair, computer terminal, assorted papers, books, and files)	1310 1365	713
Square Base Wood Crib (0.61 m cube, six sticks per layer, 16 layers, each stick with dimensions, 38 mm x 38 mm x 610 mm)	715 650	375 560

Table 1. Decay Time Constants for Fire Suppression of Furnishings

Wood Crib	Spray Density (mm/s)	Q_{act} (kW)	Decay Time Constant (s)
305 mm, [38.1 mm x 6 x 8 x 16]	0.026	198	543 [499-575]
305 mm, [38.1 mm x 6 x 8 x 16]	0.034	257	391 [358-423]
305 mm, [38.1 mm x 6 x 8 x 16]	0.041	232	195 [152-217]
305 mm, [38.1 mm x 6 x 8 x 16]	0.053	217	380 [326-402]
305 mm, [38.1 mm x 6 x 8 x 16]	0.057	232	239 [217-271]
305 mm, [38.1 mm x 6 x 8 x 16]	0.067	181	95 [76-95]
305 mm, [38.1 mm x 6 x 8 x 16]	0.081	200	44 [32-44]
305 mm, [38.1 mm x 6 x 8 x 16]	0.085	189	57 [33-57]
305 mm, [38.1 mm x 6 x 8 x 16]	0.084	256	83 [65-87]
305 mm, [38.1 mm x 6 x 8 x 16]	0.133	220	44 [22-65]
610 mm, [38.1 mm x 6 x 16 x 16]	0.066	387	478 [456-521]
610 mm, [38.1 mm x 6 x 16 x 16]	0.081	439	326 [304-347]
610 mm, [38.1 mm x 6 x 16 x 16]	0.084	413	282 [250-304]
610 mm, [38.1 mm x 6 x 16 x 16]	0.126	426	108 [76-119]

Table 2. Decay Time Constants for Wood Crib Fire Suppression

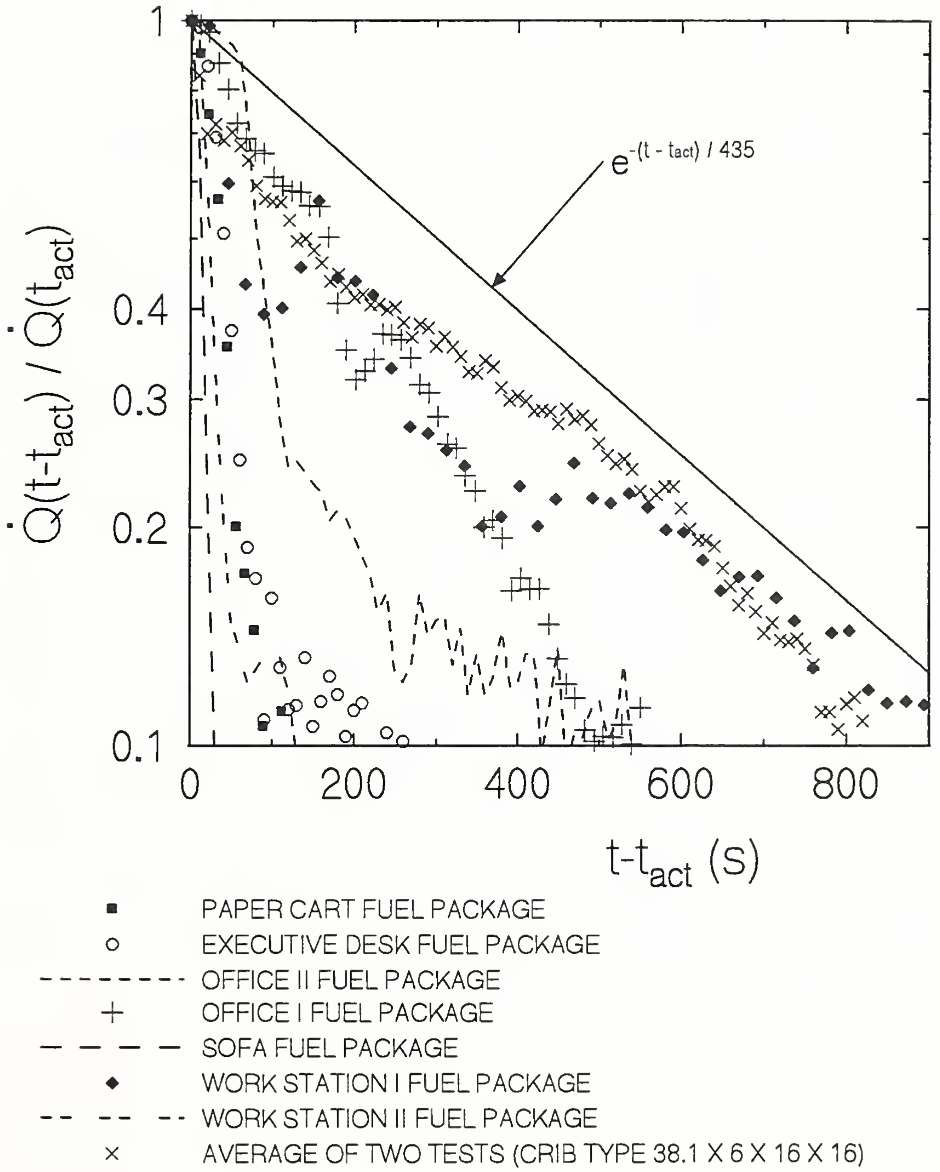

Figure 1. Heat release reduction during suppression of furnishing fires [8]

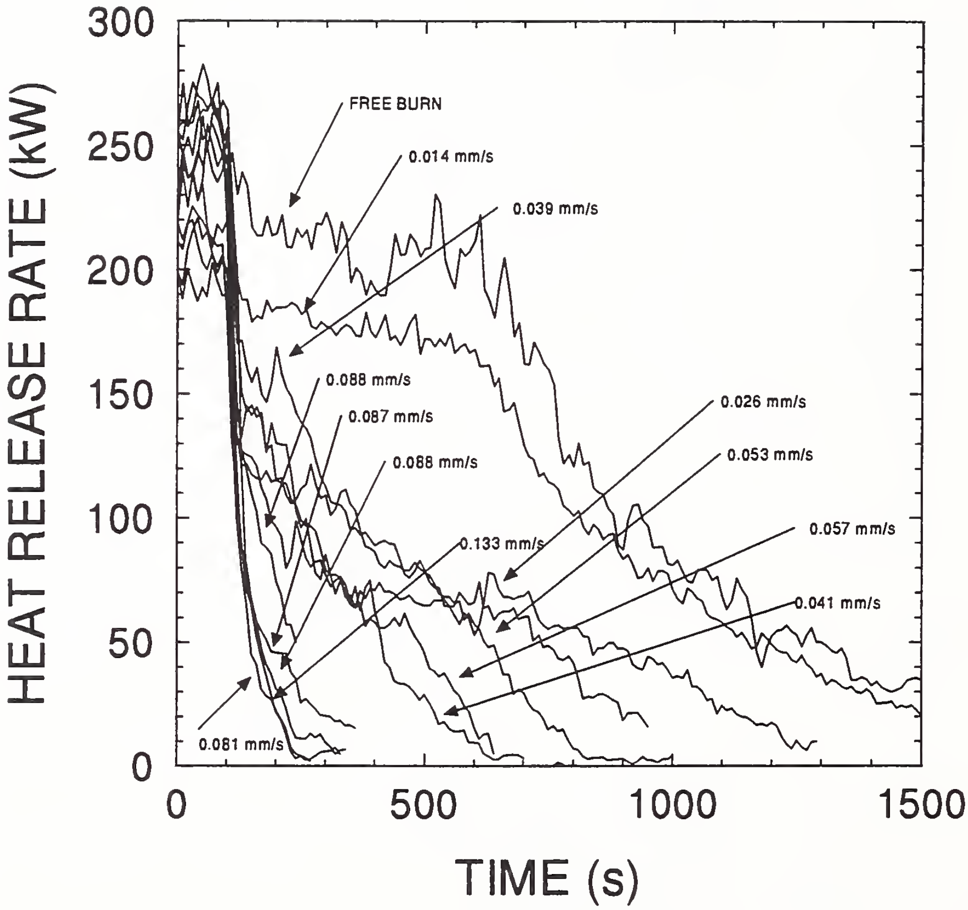

Figure 2. 305 mm wood crib heat release rates at varying spray densities [9]

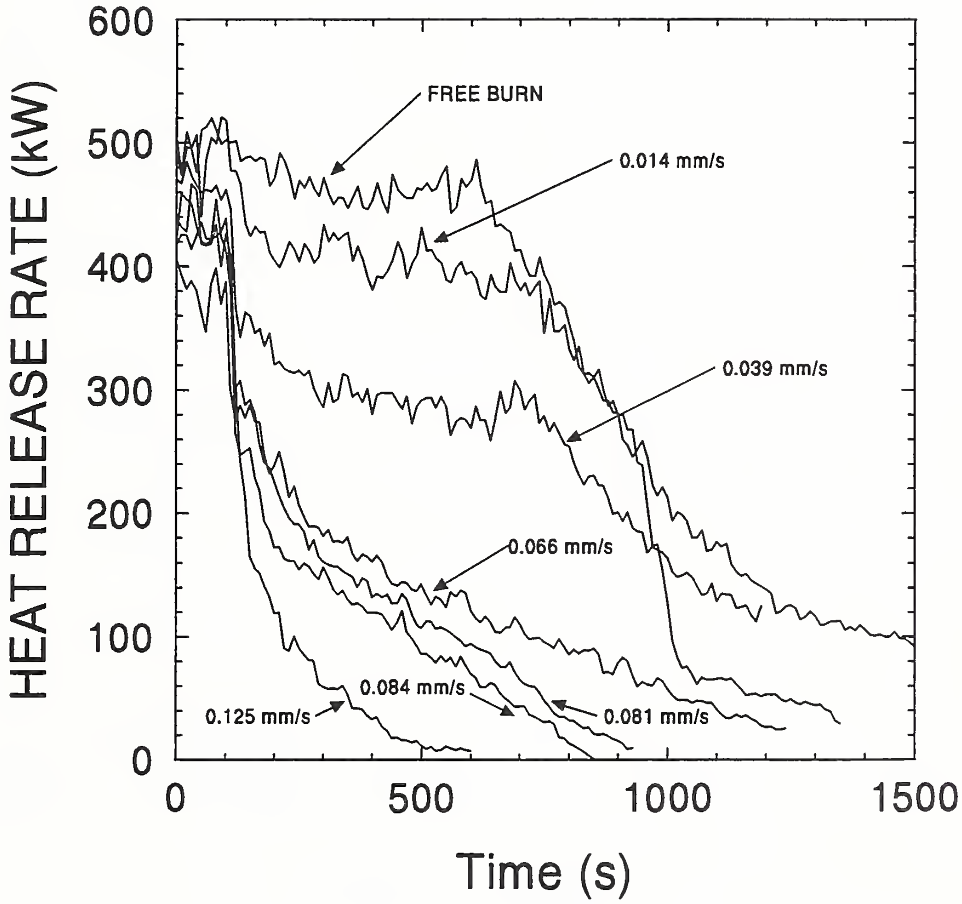

Figure 3. 610 mm wood crib heat release rates at varying spray densities [9]

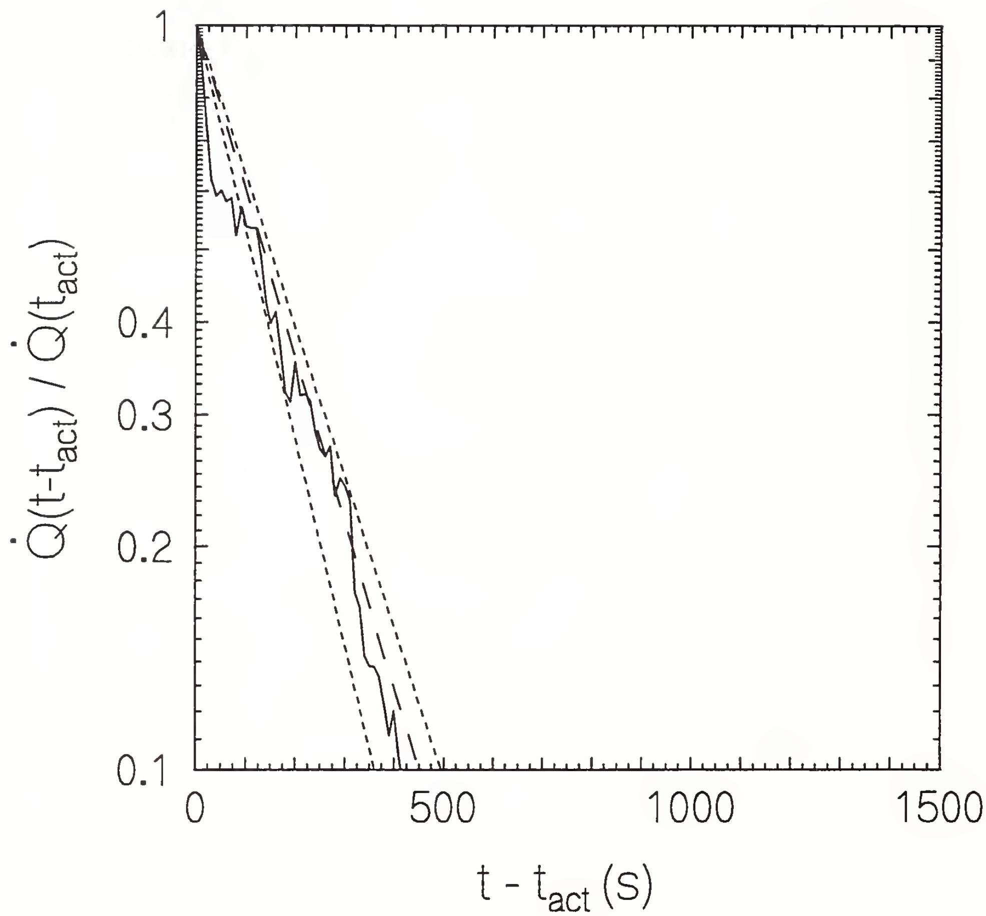

Figure 4. Time constant for 305 mm wood crib fire suppression at 0.041 mm/s sprinkler spray density

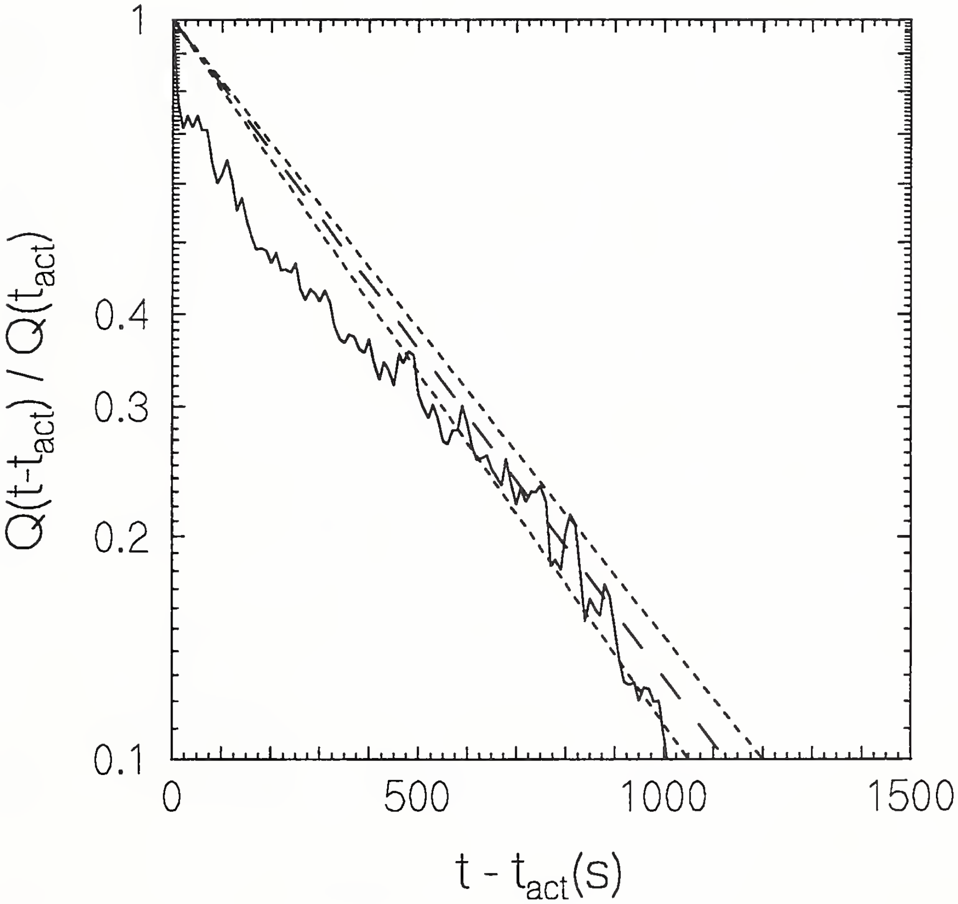

Figure 5. Time constant for 610 mm wood crib fire suppression at 0.066 mm/s sprinkler spray density

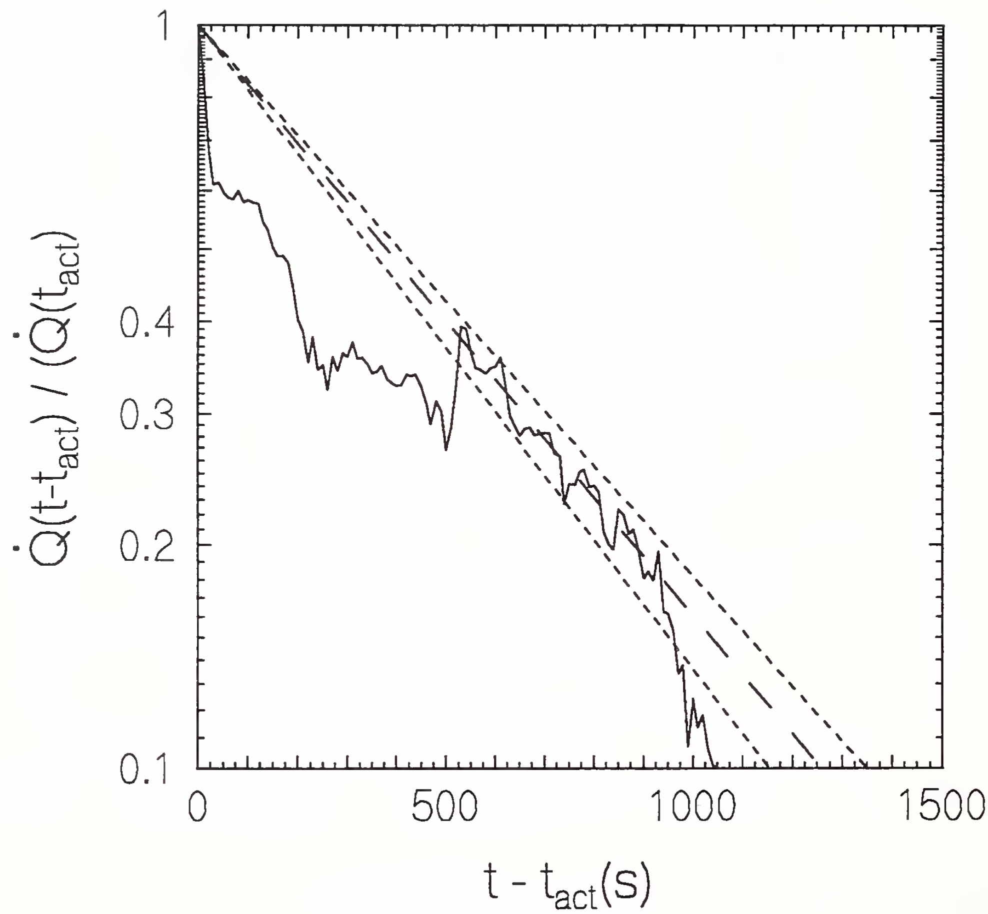

Figure 6. Time constant for 305 mm wood crib fire suppression at 0.026 mm/s sprinkler spray density

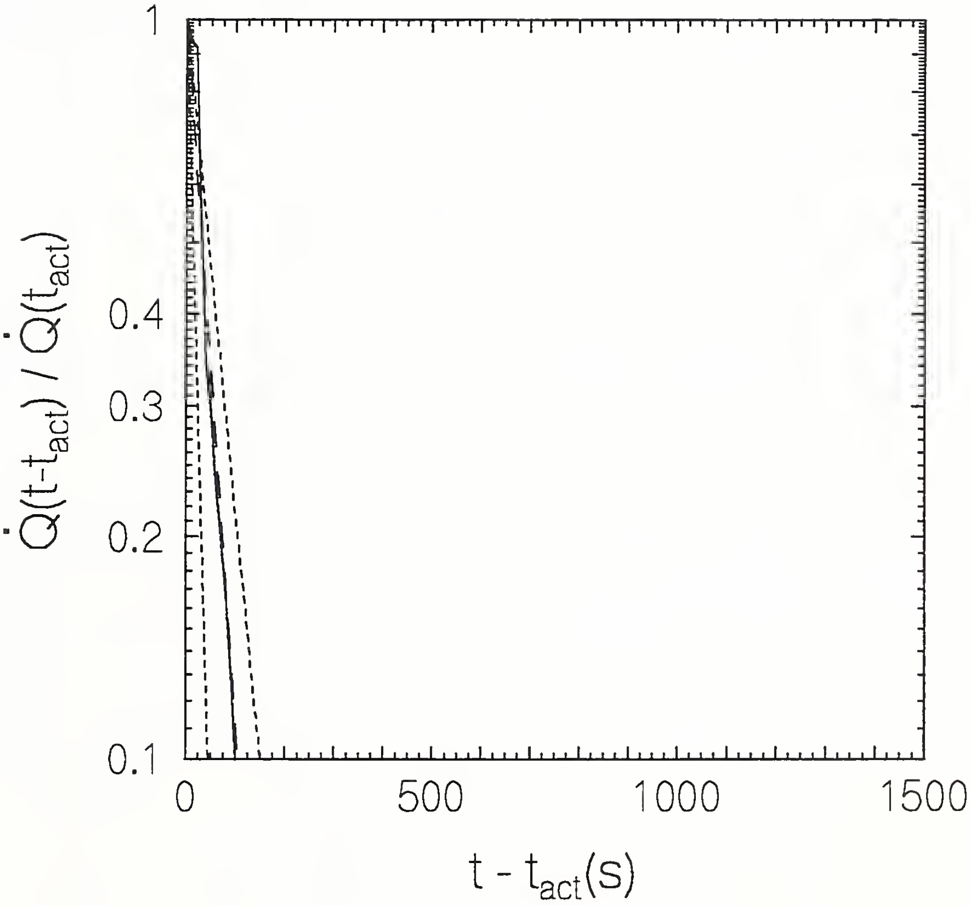

Figure 7. Time constant for 305 mm wood crib fire suppression at 0.133 mm/s sprinkler spray density

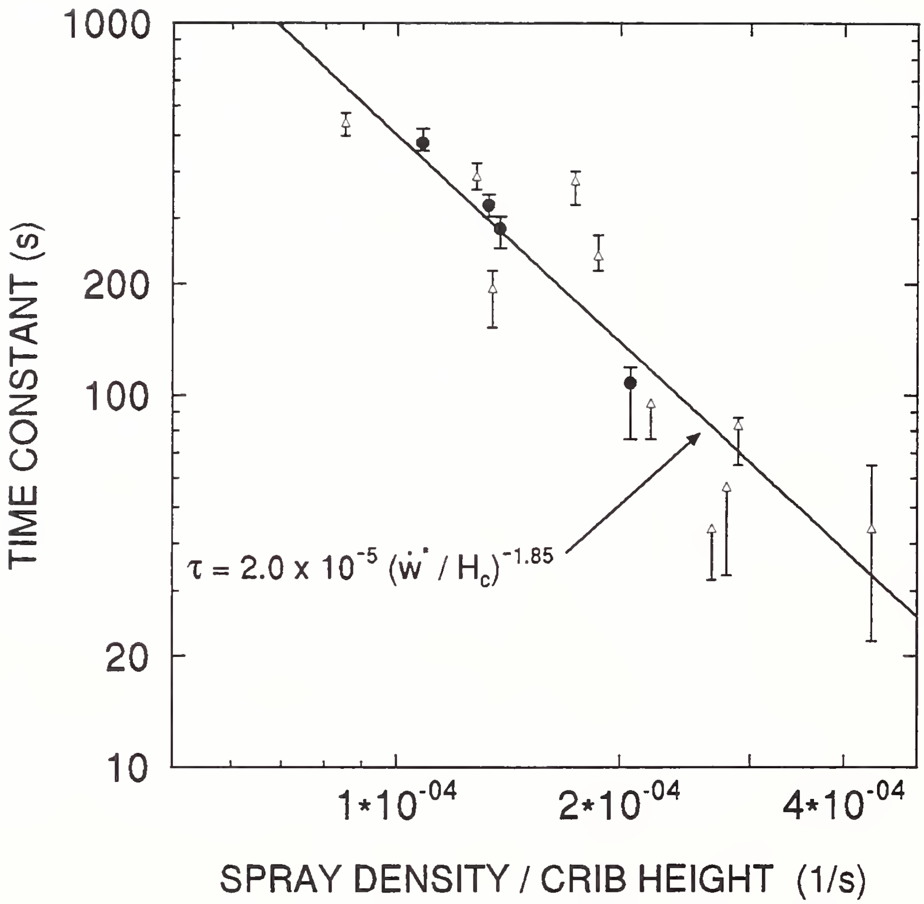

Figure 8. Effect of sprinkler spray density on the time constant for fire suppression of wood cribs (open triangles are 305 mm cribs and filled circles are 610 mm cribs)

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Measurements of the heat release rate of a fully involved square base wood crib both before and during fire suppression with water spray from commercial sprinklers were used to develop a correlation for the exponential decay time constant (τ) of the fire heat release rate from the value at sprinkler actuation. This correlation is the basis for prediction of limits for heat release rates of furnishings during fire suppression. For 0.61 m square base wood cribs that are 0.61 m in height, the time constant varies with spray density ($\dot{w}''$) as: $\tau = 3.0\ (\dot{w}'')^{-1.85}$. Using this result, the time constant for suppression at a sprinkler spray density of 0.07 mm/s is 410 s.

12. KEY WORDS (6 TO 12 ENTRIES; ALPHABETICAL ORDER; CAPITALIZE ONLY PROPER NAMES; AND SEPARATE KEY WORDS BY SEMICOLONS)

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